Nuclear Astrophysics within INFN CSN3

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1 Introduction

Nuclear astrophysics, the union of nuclear physics and astronomy, went through an impressive expansion during the last twenty years. This could be achieved thanks to milestone improvements in astronomical observations, cross section measurements, powerful computer simulations and much refined stellar models. Different fields are intimately linked together in nuclear astrophysics. As matter of fact, nuclear physics is shaping the Universe from the structure of the nuclei to the abundances of the chemical elements during BBN and later in stars and galaxies, from nuclear reactions to birth, life and death of the stars. In this report we will first discuss the astrophysical scenarios where nuclear astrophysics plays a key role, shortly describing the CSN3 activities which are addressing each of the different scenarios. Then, we will provide rather detailed status and prospects of the experiment of CSN3 belonging to the sector Nuclear Astrophysics (AsFiN, ERNA, LUNA and n-TOF) and of a few experiments, not belonging to the sectors Nuclear Astrophysics, which are contributing or will contribute to nuclear astrophysics (ALICE, GAMMA, PANDORA and SPES). As we shall see, CSN3 groups are giving quite important contributions to every domain of nuclear astrophysics, sometimes being the leaders of worldwide unique experiments.
2 Big Bang Nucleosynthesis

2.0.1 BBN @CSN3

A few reactions of the BBN network have been studied by LUNA inside the energy region of astrophysical interest taking advantage of the Gran Sasso background suppression: \( ^{3}\text{He}(\alpha,\gamma)^{7}\text{Be} \) and \( D(\alpha,\gamma)^{6}\text{Li} \). Results are expected in the near future by LUNA on \( D(p,\gamma)^{3}\text{He} \) and by AsFiN with the Trojan Horse Method (THM) on \( ^{3}\text{He}(\alpha,\gamma)^{7}\text{Be}, ^{3}\text{He}(n,p)^{3}\text{H}, ^{7}\text{Be}(n,\alpha)^{4}\text{He} \) and \( ^{7}\text{Be}(n,p)^{7}\text{Li} \). THM is a powerful indirect method, which requires normalization to high energy data but which allows for the exploration of the very low energy region also removing the electron screening effect. \( ^{7}\text{Be}(n,\alpha)^{4}\text{He} \) and \( ^{7}\text{Be}(n,p)^{7}\text{Li} \) have been directly measured in a wide energy region by n-TOF.

The published results of all these experimental efforts have excluded the nuclear solution to the controversial cosmological \( ^{6}\text{Li} \) problem and have ruled out the neutron-induced reactions as potential explanation of the cosmological \( ^{7}\text{Li} \) problem. Furthermore, PANDORA will also study in the future the electron-capture decay of \( ^{7}\text{Be} \), the father of \( ^{7}\text{Li} \), inside the plasma of a magnetic plasma trap.
3 Nucleosynthesis in hydrostatic burning phase
4 Explosive Nucleosynthesis
5 Equation of State of Ultra-dense matter
6 Nuclear experiments

6.1 AsFiN

The AsFiN group has been active in the field of nuclear astrophysics since the early 90s, mostly using indirect methods to measure nuclear reaction cross sections of astrophysical interest. The focus on indirect methods has also implied extensive investigations of reaction mechanisms, whose understanding is pivotal in relation to the application of nuclear reaction models to the extraction of the cross sections of astrophysical importance. Such investigations have been carried out both theoretically and experimentally, in collaboration with scientists from over fifteen countries.

6.1.1 Experimental techniques

The main line of research of the AsFiN collaboration is the investigation of reactions of astrophysical relevance using the Trojan Horse Method (THM). In this framework, the cross section of a reaction with three particles in the exit channel is measured to deduce the cross section and, consequently, the astrophysical factor, of a reaction of astrophysical interest. In detail, a $A(x,b)B$ reaction where the involved nuclei are charged nuclei or neutrons, can be investigated by using the $A(a,bB)s$ process where particle $a$ shows a $x+n$ cluster structure. Under peculiar kinematical conditions, $a$ breakup takes place in the nuclear field of $A$ and while the participant $x$ induces the nuclear reaction of astrophysical interest, $s$ is emitted without influencing the $A(x,b)B$ sub reaction. Since $a$ breakup takes place inside $A$ nuclear field, the $A-x$ interaction is not suppressed by the Coulomb barrier penetration, which has been already overcome in the entrance channel, making it possible to reach zero energy with high precision. More details are given in [89].

Similar considerations apply to the ANC, which has been shown to have a tight connection with THM [53]. In this case, the transfer to a bound state is studied to extract the ANC and calculate the cross section of radiative capture reactions at energies well below the Coulomb barrier [89].

The use of indirect methods makes it possible to perform high accuracy measurements with generally simple experimental setups, thanks to the large energies and yields of the indirect process to be investigated. In the case of reactions induced by radioactive nuclei, the problem of the vanishing signal-to-noise ratio is even more severe owing to the low beam intensities currently available. In this case, also the application of indirect methods calls for more complicated, large-surface detection arrays such as TECSA [70] and ASTRHO [26]. In particular, the Thick-Target Inverse Kinematics (TTIK) approach [11] has turned out very useful to measure a whole excitation function of an elastic scattering process especially involving radioactive nuclei, allowing one to perform nuclear spectroscopy of states involved in peculiar astrophysical scenarios (see, for instance, [88]).

Finally, the availability of high-power lasers and of high-resolution, high-luminosity $\gamma$-beams will open new opportunities in nuclear astrophysics. First, petawatt lasers allow us to induce nuclear reactions in hot plasmas, similar to the ones in astrophysical environments. Therefore, it is possible to study [73] nuclear reactions under astrophysical conditions, accounting for, e.g., electron screening effects. Moreover, thanks to the large number of interacting ions, it would be possible to perform direct measurements of reaction cross sections down to the energies where such reactions take place in stars. The
availability of high-intensity lasers has also made it possible to produce high-resolution \( \gamma \)-beams of intensities larger than \( 10^6 \gamma/s \) by means of Compton back-scattering of laser light off an accelerated counter-propagating fast electron beam. Therefore, photodissociation reactions occurring in the presupernova stage and in the p-process will be studied, as well as radiative capture reactions through the detailed balance principle (for ground-state to ground-state transitions). A 4\( \pi \) silicon detector array is under development in collaboration with ELI-NP [52].

6.1.2 Current Nuclear Astrophysics measurements

The AsFiN group is currently active in several astrophysical context such as the primordial nucleosynthesis, hydrostatic burning phase nucleosynthesis, s-process, classical novae. Here is a comprehensive scheme of the present activities:

- The astrophysical S(E)-factor for the \( ^3\text{He}(\alpha,\gamma)^7\text{Be} \) reaction, which is important for the Big Bang Nucleosynthesis (BBN) and the H-burning in stellar interiors was investigated by means of the ANC technique. The experiment was performed in Florida State University in late 2017 and presently under analysis. Data will be extracted in the region of astrophysical interest, as shown by the simulations. Once the reaction rate is calculated from the present data, after comparison with other measurements (direct and indirect) the astrophysical implications will be evaluated.

- The study of the \( ^3\text{He}(n,p)^3\text{H} \) reaction to be measured via THM in Notre Dame University in 2018 is also relevant for the primordial nucleosynthesis. The possibility, given by the THM, to investigate neutron induced reactions was already tested in the past years [46], and will allow us to retrieve information on the S(E)-factor in the Gamow energy range.

- In the BBN framework AsFiN has performed two experiments in recent years to investigate the \( ^7\text{Be}(n,p)^7\text{Li} \) and the \( ^7\text{Be}(n,\alpha)^4\text{He} \) processes. Experiments were performed at INFN-LNL and at CNS-RIKEN where the radioactive ion beam was produced. Data analysis is still in process and THM offers the great possibility to measure cross section of RIB interaction with neutrons.

- The \( ^{23}\text{Na}(p,\alpha)^{20}\text{Ne} \) reaction is one of the most interesting processes in astrophysics since it is of primary importance for sodium destruction inside stars and for the nucleosynthetic path in the \( A \geq 20 \) mass region. This reaction is also involved in the branching point of the NeNa cycle, responsible of steady hydrogen burning at high temperatures, and is especially important for the understanding of the O-Na anti-correlations in massive stars. The measurement has been recently carried out at LNS tandem using the first \( ^{23}\text{Na} \) beam in Europe and data analysis is ongoing.

- The \( ^{27}\text{Al}(p,\alpha)^{24}\text{Mg} \) reaction drives the destruction of \( ^{27}\text{Al} \), the production of \( ^{24}\text{Mg} \) and closes the MgAl cycle when its rate exceeds that of the competitor reaction \( ^{27}\text{Al}(p,\gamma)^{28}\text{Si} \). The experiment, performed by using the THM was completed in March 2018 at LNS tandem. Data analysis has just started.

- Low-energy fusion reactions involving \( ^{12}\text{C} \) and \( ^{16}\text{O} \) are of great astrophysical importance for our understanding of the timescale and the nucleosynthesis during late stellar evolution of massive stars \( (M \geq 8 \) solar masses). Fusion processes like \( ^{12}\text{C}+^{12}\text{C} \),
\[ ^{12}\text{C} + ^{16}\text{O} \text{ and } ^{16}\text{O} + ^{16}\text{O} \text{ depends not only on the reaction rate but also on the branching between proton, neutron, or } \alpha \text{ decay channels. They play also a pivotal role in the ignition of type Ia supernova stars and of explosive burning processes in the atmospheres of accreting neutron stars. This is a very interesting research topic as it is demonstrated by the Letter published in Nature by AsFiN on the pioneering study of the } ^{12}\text{C} + ^{12}\text{C} \text{ fusion reaction [90].} \]

- In the framework of the AGB nucleosynthesis investigation and in particular regarding the destruction of \(^{19}\text{F}\) in cosmic environments, the \(^{19}\text{F}(p,\alpha)^{16}\text{O}\) and \(^{19}\text{F}(\alpha,p)^{22}\text{Ne}\) have been studied via the THM. Our results shed light, for the first time, on poorly known resonances at astrophysical energies. Moreover, after successfully completing the investigation of the \(^{13}\text{C}(\alpha,n)^{16}\text{O}\) reaction, by supplying a robust reaction rate accounting for direct and indirect measurements, AsFiN has focused on the \(^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}\) reaction (measurement completed in March 2018) which produces neutrons for massive stars. Also, we are presently studying the \(^{14}\text{N}(n,p)^{14}\text{C}\) reaction which is the principal neutron poison in AGB’s.

- Explosive nucleosynthesis in classical novae is under investigation by the AsFiN group. In particular the \(^{18}\text{F}(p,\alpha)^{15}\text{O}\) reaction was studied in recent years and needs further investigations especially for measuring the angular distributions. \(^{18}\text{F}\) decays in the moment when the nova envelope becomes transparent to radiation thus its \(\gamma\)-emission and therefore its abundance may probe the structure and nucleosynthesis in details.

- Together with the measurements performed via indirect methods reactions of astrophysical interest are also induced in laser-driven plasma. The \(d(d,p)t\) and \(d(d,n)^{3}\text{He}\) are presently studied after cluster Coulomb explosion in laser-induced plasma. Data analysis is still in progress.

- Photodissociation play a crucial role in many astrophysical environments such as supernovae, massive stars, BBN and p-processes. For a prospective use of the \(\gamma\)-beam in ELI-NP a first experiment, investigating \(^{7}\text{Li}(\gamma,\alpha)^{3}\text{H}\), has been recently performed at HIGS (TUNL) in the astrophysical energy range.

### 6.1.3 Future Nuclear Astrophysics measurements

The AsFiN collaboration will pursue, on one hand, the investigation of nuclear reaction of astrophysical interest using indirect methods. On the other, we will keep our commitment to find novel solutions for accessing astrophysical conditions in the laboratory.

- Using the THM and the stable beams available at the Laboratori Nazionali del Sud (Catania) including, in the next years, noble gases and pulsed beams, we will study the reactions influencing the evolution and nucleosynthesis of massive stars, precursors of supernovae and neutron stars, which are the object of the investigation of multimessenger astronomy. Following the successful work on the \(^{12}\text{C} + ^{12}\text{C}\) fusion [90], we aim at measuring the \(^{12}\text{C} + ^{16}\text{O}\) and \(^{16}\text{O} + ^{16}\text{O}\) fusion cross sections and the branching to the different channels. For the study of nucleosynthesis in massive stars, we will continue the investigation of the reactions involved in the NeNa and MgAl cycles and, with the forthcoming noble gases ion source, we will complete our investigation of the \(^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}\) reaction.
Radioactive nuclei play a major role in astrophysics, especially in the case of explosive scenarios. These include long-lived species, having half-lives so large to allow for the production of a target for a sputtering source, such as $^{10}$Be ($T_{1/2} = 1.5 \times 10^6$ y), $^{26}\text{Al}_{g.s.}$ ($T_{1/2} = 7.2 \times 10^5$ y), $^{36}\text{Cl}$ ($T_{1/2} = 3.0 \times 10^5$ y), and short lived species for which ISOL or in-flight RIB facilities are necessary for their use as beam. AsFiN, in collaboration with the LNS staff and international laboratories such as PSI (Switzerland) or ATOMKI (Hungary), has positively tested the possibility to accelerate long-lived species and has proposed the indirect measurements of the $^{10}\text{Be}(\alpha, n)^{13}\text{C}$, of the $^{26}\text{Al}(n, \alpha)^{23}\text{Na}$ and of the $^{26}\text{Al}(n, p)^{26}\text{Mg}$ reactions using the THM at LNS (in the case of $^{26}\text{Al}$ for the ground state only), of great importance in the understanding of the solar system formation.

In the case of short-lived radioactive nuclei, AsFiN aims at investigating mainly reactions influencing our understanding of the sources targeted by multimessenger astronomy. For instance, the investigation of Type I X-ray bursts would help to constrain neutron star models. Among the reactions of interest, we consider the $^{14}\text{O}(\alpha, p)^{17}\text{F}$ and the $^{18}\text{Ne}(\alpha, p)^{21}\text{Na}$ that could be the onset of a possible route that breaks out from the HCNO cycles, and the $^{34}\text{Ar}(\alpha, p)^{37}\text{K}$, since $^{34}\text{Ar}$ is a waiting point in X-ray bursts nucleosynthesis. As long as SPES will not be available, we plan to perform these measurements at LNS using the FRIBS facility [80] and at other RIBs facilities such as CRIB-RIKEN and MARS-TAMU; then, we plan to shift our research activity on RIBs to SPES, owing to the foreseen intensities and beam quality. In particular, we have an accepted LOI about measurements involving $^{26}\text{Al}^{m}$ (isomeric state at 228 keV, $T_{1/2} = 6.35$ s) beam, for studying the $^{26}\text{Al}^{m}(n, \alpha)^{23}\text{Na}$ and the $^{26}\text{Al}^{m}(n, p)^{26}\text{Mg}$ reactions by means of the THM, using a deuteron to transfer a neutron. We would like to underscore that $^{26}\text{Al}^{m}$ should be the first beam delivered by SPES using the SiC production target. At SPES, we also plan to measure a number of $(n, p)$, $(n, \alpha)$ and $(n, \gamma)$ reactions of interest for the r-process using the THM and the ANC techniques. Finally, a developing activity making use of radioactive nuclei is the investigation of $\beta$-delayed neutron emission [67]. Indeed, during the r-process after freeze-out some nuclei may be populated in neutron unbound states following $\beta$-decay.

Regarding fusion reactions in a laser-induced hot plasmas, we aim at extending the physical cases investigated so far. Next scheduled measurements are the $^{10}\text{B}(p, \alpha)^{7}\text{Be}$ and the $^{11}\text{B}(p, \alpha)^{8}\text{Be}$ reactions, of interest for the electron screening problem and for aneutronic fusion in terrestrial fusion reactors.

The availability of high-resolution and high-intensity $\gamma$-beam has triggered the interest for a number of direct and indirect measurements. Regarding direct measurements, they play a substantial role in stellar advanced evolutionary stages, such as silicon burning before the onset of core collapse supernova or the p-process. Scheduled measurements are the $^{24}\text{Mg}(\gamma, \alpha)^{20}\text{Ne}$ governing the downward flow from $^{24}\text{Mg}$ to $\alpha$’s, the $(\gamma, p)$ reactions on $^{74}\text{Se}$, $^{78}\text{Kr}$, $^{84}\text{Sr}$, $^{92}\text{Mo}$, and $^{96}\text{Ru}$, as well as the the $^{96}\text{Ru}(\gamma, \alpha)^{92}\text{Mo}$ reaction.
6.1.4 Expected improvements in comparison with literature

The driving idea of the AsFiN experimental program is to devise methods and adopt procedures allowing us to approach as much as possible the same conditions as in the astrophysical scenarios under investigation. To this purpose, we make use of either indirect techniques or resort to novel experimental apparatuses, such as high-power lasers and $\gamma$-beams. This way, AsFiN could get a deeper look inside most of the astrophysical phenomena we have investigated. For instance, in [90], we could explore for the first time the astrophysical energy range of $^{12}\text{C}+^{12}\text{C}$. This is a significant step forward in comparison with existing direct data [8, 13, 48, 51, 63].

![Figure 1: The C+$^{12}\text{C}$ astrophysical S(E)* factor for the $^{20}\text{Ne}+\alpha_1$ channel. The upper and lower grey lines mark the range arising from 1$\sigma$ uncertainties on resonance parameters plus the normalization to direct data. Direct data are reported as symbols ([90] for details.)](image)

6.1.5 International competition

Activity performed by AsFiN is leading the field in the context of indirect measurements for applications to nuclear astrophysics. THM and ANC give more and more reliable data in the Gamow energy range to the astrophysics community in many cosmic scenarios. Synergy is required with direct measurements especially for the normalization procedure at higher data. Moreover in many other contexts, e.g. in explosive scenarios where the interaction between neutrons and exotic beams has to be studied at astrophysical energies, indirect methods give a unique possibility. Even large and important collaborations and facilities like LUNA, JUNA, $N_{TOF}$ etc have limited possibilities for those scenarios.
6.2 ERNA

The European Recoil Separator for Nuclear Astrophysics (ERNA) is a tool for the measurement of the total cross section of capture reactions of astrophysical interest. It was originally commissioned at the Dynamitron Tandem Laboratorium of the Ruhr-Universität Bochum, Bochum, Germany [40, 76–78, 83]. Its design was focussed to the measurement of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ in a wide energy range [77]. The excellent results on the total cross section of this reaction [82, 85] were complemented with measurements of the cascade transitions [84]. Significant advances were also brought to the understanding of the $^{3}\text{He}(\alpha, \gamma)^{7}\text{Be}$ process [30, 32, 33].

In 2009 ERNA was transferred to the Center for Isotopic Research on Cultural and Environmental heritage (CIRCE) of the Università della Campania/Innova. This gave the opportunity for a significant upgrade of the apparatus. The separator in its present layout is shown in Figure 2.

![Figure 2: Layout of the ERNA recoil separator at the CIRCE Laboratory.](image)

In addition to the measurements with the recoil separator, the scientific activities of the ERNA Collaboration include also measurements with an array of double stage detectors (GASTLY), and the mass spectrometry of meteoritic samples, as well as other measurements that make use of the intense $^{7}\text{Be}(p, \gamma)^{8}\text{B}$ reaction.

6.2.1 Experimental techniques

**On line recoil mass separation** The recoil separator technique allows the total cross section measurement of radiative capture reaction cross sections through the direct detection of the recoil nuclei produced in the fusion process. Although simple in principle, the technical challenges involved in its setup are enormous.

The reaction is initiated in a windowless gas target differentially pumped on both sides. A number of gas targets were developed for the different reaction studied: extended $^{4}\text{He}$ [31, 40, 83], extended $^{3}\text{He}$ with gas recirculation [32], extended $^{1}\text{H}_2$ [84] and supersonic jet $^{4}\text{He}$ [74].

The recoils emerging from the target are transported, for a selected charge state, to the end
detector, while the primary beam is suppressed by many orders of magnitude \((10^{10} - 10^{15})\) allowing for direct identification and counting of the reaction products with either a Ionization Chamber Telescope or Time of Flight-Energy detection system. For each reaction under study the transport of the recoils through the separator is ensued by transporting a beam with the same rigidity expected for the recoils, with maximum angle expected for them to emerge from the target, and experimentally determining the separator elements fields.

**Charged particle spectroscopy** The study of the \(^{12}\text{C} + ^{12}\text{C}\) fusion process was initiated long ago with a relatively simple setup [92]. An high intensity beam, \(\sim 10\,\mu\text{A}\), impinging on an thick graphite target, while charged particles are detected in detector telescopes at backward angles. That study approached the lowest measurement energies, however the limitations of the approach appeared clear, some were connected to the detection setup, the alpha particles could not be observed due to limitations of the \(\Delta E\) detectors used, and some were connected to the background due to the hydrogen contained in traces in the graphites used as targets.

To improve the situation, a thorough study of the behaviour of the target and the contaminant hydrogen under high current ion beam bombardment was conducted [64–66]. To proceed with measurements towards the astrophysically relevant energies the ERNA Collaboration has developed a detection array GAs-Silicon Two-Layer sYstem (GASTLY) hosted in a large volume scattering chamber. It has been designed to detect and identify low-energy light particles emitted in nuclear reactions of astrophysical interest. Devoted to the measurement of nano-barn cross-sections, the system is optimised for large solid angle coverage and for low-energy detection thresholds. The array consists of eight modules, each comprising an ionisation chamber (\(\Delta E\)) and a large area silicon strip detector (\(E_{\text{rest}}\)). Its modularity and versatility allow for use in a variety of experiments for the detection and identification of light charged particles.

**Isotopic ratio mass spectrometry** The \(^{60}\text{Fe}\) and the \(^{107}\text{Pd}\) present in the early solar system, \(\beta^-\) decayed to \(^{60}\text{Ni}\) and \(^{107}\text{Ag}\), with half lives of 2.62 My and 6.5 My, respectively. The measurement of the ratios of Ni and Ag isotopes abundance in meteorite samples provides information on the stellar event that generated the solar system. Such measurements can be performed to high accuracy with the Multicollector-Inductively Coupled Plasma Mass Spectrometer (MC-ICP-MS) present at the CIRCE Laboratory. In fact, the Inductively Coupled Plasma (ICP) source has a very high extraction efficiency (\(> 40\%\)), that in conjunction with the multicollector, allows measurements in high resolution \(M/\Delta M \approx 400\). In addition, this methodology can be also applied to metalloids and non-metals, greatly extending the number of isotopes that can be potentially measured.

### 6.2.2 Current Nuclear Astrophysics measurements

**Recoil separator** The cross section determination of \(^{7}\text{Be}(p,\gamma)^{8}\text{B}\) was recently completed, the procedures and results of a test measurement are presented in [21]. After this measurement the extended \(^{1}\text{H}_2\) target was replaced by the \(^{4}\text{He}\) supersonic jet gas target, actually starting the measurement campaign of the \(^{12}\text{C}(\alpha,\gamma)^{16}\text{O}\), for which some of the ancillary measurements have already been performed (separator tuning, post-stripper characterization, charge state probability, etc.). In parallel also the \(^{14}\text{N}(\alpha,\gamma)^{19}\text{F}\) and the
\(^{15}\text{N}(\alpha, \gamma)^{19}\text{F}\) will be also investigated. The first one has already been studied with the extended \(^4\text{He}\) target \([31]\). The narrow resonances below 1 MeV will be measured including the most relevant at 364 keV, known only through indirect methods, although this might be very challenging due to the extremely low expected counting rate (~1 recoil/day).

Since at CIRCE is available a very intense beam of \(^7\text{Be}\) with tandem quality, to complement the \(^7\text{Be}(p, \gamma)^8\text{B}\) measurement, the elastic scattering process \(^7\text{Be}(p, p)^7\text{Be}\) is also being studied.

**Charged particle spectroscopy** After a long phase of detector development and target characterization, a first measurement campaign of the \(^{12}\text{C} + ^{12}\text{C}\) has been completed in the energy range \(E_{\text{c.m.}} = 2.3 - 4.5\) MeV. Measurements toward \(E_{\text{c.m.}} = 2.0\) are ongoing. Concurrently, thanks to a further detector development that allows the use of silicon strip detectors as \(E_{\text{rest}}\) detectors, angular distributions of the emitted charged particles are being measured at \(E_{\text{c.m.}} \sim 4\) MeV.

**Meteorites** The extraction procedures for both Ni and Ag, have been developed and charactherized using standard certified materials.

The first samples directly measured are two ferritic meteorites, the Brenham and the Mineo pallasites. The first one is a meteorite already studied and is therefore used as a benchmark for the developed methodology. The only available sample of the Mineo pallasite is present at the Dipartimento di Fisica e Geologia of the Universit di Perugia. The morphological and chemical characterization of this sample has been the preliminary step toward the isotopic abundance ratios measurements \([93]\).

### 6.2.3 Future Nuclear Astrophysics measurements

The future scientific program of ERNA will be detailed next year. It will include the study of the \(^{16}\text{O}(\alpha, \gamma)^{20}\text{Ne}\) and \(^{33}\text{S}(p, \gamma)^{34}\text{Cl}\). It might still include the \(^{12}\text{C}(\alpha, \gamma)^{16}\text{O}\) reaction, depending on the results of the present campaign.

As for charged particle spectroscopy, the study of \(^{12}\text{C} + ^{12}\text{C}\) might be continued also in view of the recent results obtained with the Trojan Horse Method. Also the study of the \(^{12}\text{C} + ^{16}\text{O}\) fusion processes is being considered.

The present studies of meteorites was concentrated on bulk material, in the near future it will be extended to inclusions, mostly olivines as regards the pallasites, and Calcium-Aluminum inclusions (CAI) in chondrite samples. The study of CAIs will require the development of protocols for the preparation and measurement of \(^{26}\text{Mg}\) and \(^{41}\text{K}\), relics of \(^{26}\text{Al}\) and \(^{41}\text{Ca}\), respectively.

In addition, we plan to start some measurements of the \(^7\text{Be}\) half life, neutral and ionized, is different environments. Also the measurement of \(^7\text{Be}(\alpha, \alpha)^7\text{Be}\) elastic scattering has been proposed by the Notre Dame University group and a feasibility study is undergoing.

### 6.2.4 Expected improvements in comparison with literature

Concerning the measurements with the recoil separator, the measurement of the total cross sections allows to put in evidence components difficult to be identified through \(\gamma\)-ray spectroscopy, e.g. non radiative and/or weak cascade transitions, as in the case of
\[ ^{12}\text{C}(\alpha, \gamma)^{16}\text{O} \] [83, 84]. In addition, the use of a technique with systematics quite different from previous measurements, can in general improve the accuracy of global analysis cross section determinations.

More in detail, for the \[ ^{12}\text{C}(\alpha, \gamma)^{16}\text{O} \] the measurement of the cross section down to \( E_{\text{c.m.}} \sim 1 \text{ MeV} \), with the concurrent measurement of \( \gamma \)-rays and \( e^+e^- \) pairs at selected energies, will allow for more precise and accurate extrapolations to astrophysical energies.

In the \[ ^{12}\text{C}+^{12}\text{C} \] study we aim to reach energies around 2 MeV, improving the statistical precision of the data. Concurrently the measurement of angular distributions at higher energies might help in better identifying the parameters of resonances involved in the fusion process.

As concerns the meteorites studies, there are not many groups measuring isotopic ratios, especially for Ni. Therefore, we expect to contribute to lower systematic uncertainties through the intercomparison with similar measurements. Moreover we plan to extend measurements to samples not studied before.

### 6.2.5 International competition

Several recoil separators devoted to the measurement of cross section of astrophysical interest are present around the world, see e.g. [79] for a review.

The DRAGON recoil separator at TRIUMF Vancouver, Canada, is the most active. Originally designed for the measurement of reactions involving radioactive ion beams (RIB), has also measured over the years a number of reactions with stable nuclei. Given the limited acceptance of this separator only a moderate number of reaction can be meaningfully measured there.

The Daresbury Recoil Separator at the Holifield Radioactive Ion Beam Facility of the Oak Ridge National Laboratory, TN USA, is operational since 1997, however only a limited number of proton capture reactions have been studied. Its status at present is unclear.

The St. George recoil separator has been recently installed at the University of Notre Dame, IL USA. Equipped with a \(^4\text{He} \) jet gas target, it is devoted to measurements of reactions involving stable isotopes. At present is still in commissioning phase.

At the Kiushu University Tandem Laboratory, Kiushu Japan, was present a separator optimized for the study of the \[ ^{12}\text{C}(\alpha, \gamma)^{16}\text{O} \] reaction. The separator has been recently disassembled for laboratory rebuilding works. It is unclear whether it will be reassembled and if other reactions are in the scientific program.

A few projects have been announced regarding recoil separators for Nuclear Astrophysics, mostly related to new RIB facilities, however they might also be used with stable beams:

- The Separator for Capture Reactions (SECAR) at ReA3 (low-energy reaccelerated beams) at the Facility for Rare Isotope Beams (FRIB) at Michigan State University, foreseen completion 2020-2022,
- The KOREA Broad acceptance Recoil spectrometer and Apparatus (KOBRA) at the RAON Heavy Ion Accelerator complex, Daejeon, South Korea. Completion foreseen in 2021.

As for \[ ^{12}\text{C}+^{12}\text{C} \], although there is large interest on this reaction, the only ongoing measurement we are aware of is at the University of Notre Dame. However, only a conference proceeding was published so far on this experiment [37].
6.3 LUNA

6.3.1 Experimental techniques

Underground nuclear astrophysics was born twenty-seven years ago in the core of Gran Sasso, with the aim of measuring cross sections in the low energy range and of deriving reaction rates directly at stellar temperatures. LUNA (Laboratory for Underground Nuclear Astrophysics) started its activity as a pilot project with a 50 kV accelerator [44] and it has been for about 25 years the only laboratory in the world running an accelerator deep underground, currently a 400 kV accelerator with hydrogen and helium beams [39]. The extremely low laboratory background has allowed for the first time nuclear physics experiments with very small count rates, down to a couple of events per month. Only in this way, the important reactions responsible for the hydrogen burning in the Sun could be studied down to the relevant stellar energies [19, 27]. In particular, the first direct determination of the cross section of $^3\text{He}(^3\text{He},2p)^4\text{He}$ inside the Solar Gamow peak definitively excluded a nuclear solution to the solar neutrino problem [15] while the LUNA experiment on the bottleneck reaction of the CNO cycle, $^{14}\text{N}(p,\gamma)^{15}\text{O}$, reduced by a factor of two the value of the CNO neutrino flux expected from the Sun [38]. More recently, LUNA shed light on the origin of one group of meteoritic stardust [58] through a low-energy study of $^{17}\text{O}(p,\alpha)^{14}\text{N}$ [20]. Full descriptions of LUNA and several results are given in two recent review papers [18, 25].

6.3.2 Current Nuclear Astrophysics measurements

The 400 kV current LUNA accelerator and the unique low-background conditions of the underground LNGS laboratory have been and still are the perfect blend for the study of most of the proton-capture reactions involved in the stellar H burning and in the Big Bang Nucleosynthesis.

Among the reactions so far studied by the LUNA400 collaboration, there are various processes of the C-N-O cycle involving nitrogen and oxygen isotopes, i.e., $^{14}\text{N}(p,\gamma)$, $^{15}\text{N}(p,\gamma)$, $^{17}\text{O}(p,\alpha)$, $^{17}\text{O}(p,\gamma)$ and $^{18}\text{O}(p,\gamma)$, and some of the Ne-Na and Mg-Al cycle, i.e. $^{22}\text{Ne}(p,\gamma)$ and $^{25}\text{Mg}(p,\gamma)$. A scientific program based on the study of $D(p,\gamma)$, $^6\text{Li}(p,\gamma)$, $^{13}\text{C}(\alpha,n)$, $^{22}\text{Ne}(\alpha,\gamma)$ and $^{12,13}\text{C}(p,\gamma)$ has been approved both by INFN-CSN3 and LNGS-Scientific Committee and it will extend to the whole 2019.

Theoretical calculations of the products of the primordial nucleosynthesis (also Big Bang Nucleosynthesis, hereinafter BBN) provide important hints for cosmology and particle physics. The recent developments of experimental cosmology, such as, in particular, the precise determination of the CMB temperature fluctuations obtained by WMAP and PLANCK as well as the observation of high-redshift supernovae, revived the interest for BBN studies. In practice, different observables provide spots of the Universe at different epochs. In particular, LUNA400 has contributed to improve the predictions of the BBN by significantly reducing the uncertainties of the rates of the $^3\text{He}(\alpha,\gamma)^7\text{Be}$ and the $D(\alpha,\gamma)^{6}\text{Li}$ reactions. To complete this investigation, an accurate determination of the $D(p,\gamma)^{3}\text{He}$ reaction rate is now missing and is the goal of the ongoing experiment at LUNA400. This reaction mainly affects the primordial deuterium abundance. A precise determination of its rate at BBN energies is a necessary input to constrain baryon density and effective neutrino family number.

In view of the foreseen studies at the new LUNA MV facility, experiments on two processes
that may be active in the stellar He-burning zones, when the slow neutron capture nucleosynthesis (s process) takes place are also in progress. The first, the $^{13}$C$(\alpha,n)^{16}$O reaction, is the most important neutron source in low-mass Asymptotic Giant Branch (AGB) stars and is responsible for the production of about half of the heavy isotopes (beyond iron) in nature. The second is the $^{22}$Ne$(\alpha,\gamma)^{26}$Mg, which competes with the $^{22}$Ne$(\alpha,n)^{25}$Mg reaction, another important neutron source for massive stars, and contribute to the synthesis of Mg isotopes. The on-going program is completed by the study of the $^6$Li(p,$\gamma$)$^7$Be reaction to clarify some important nuclear physics issues and to improve the knowledge of the $^3$He$(\alpha,\gamma)^7$Be process, one of the key branches of the p-p chain. Projects on other scientific cases which could be perfectly suited for cutting-edge experiments at LUNA400 are under discussion and will be collected in an organic proposal within the end of 2019.

### 6.3.3 Future Nuclear Astrophysics measurements

A beam of higher energy is required to extend the LUNA approach to study He and C burnings. The LUNA MV project has been developed to overcome such a limit with the new 3.5 single-ended accelerator to be installed in Gran Sasso at the beginning of 2019. The accelerator will provide hydrogen, helium and carbon (also doubly ionized) high current beams and it will be devoted to the study of those key reactions of helium and carbon burning that determine and shape both the evolution of massive stars towards their final fate and the nucleosynthesis of most of the elements in the Universe. $^{12}$C+$^{12}$C and $^{12}$C$(\alpha,\gamma)^{16}$O represent the “Holy Grail” of nuclear astrophysics and they are the most ambitious goals of this project. In particular, $^{12}$C+$^{12}$C will be the flagship reaction of the first 5 year proposal of LUNA MV. This reaction is the trigger of C burning. The temperature at which C burning takes place depends on its rate: the larger the rate, the lower the C-burning temperature. Since the temperature controls the nucleosynthesis processes, reliable estimations of all the yields produced by C burning, for example the weak component of the s process which produce the elements between Fe and Sr, require the precise knowledge of the $^{12}$C+$^{12}$C rate. The $^{12}$C+$^{12}$C rate also determines the lower stellar mass limit for C ignition. This limit separates the progenitors of white dwarfs, novae and type Ia supernovae, from those of core-collapse supernovae, neutron stars, and stellar mass black holes. This mass limit also controls the estimations of the expected numbers of these objects in a given stellar population, which are required to answer crucial questions such as: how many neutrons stars are there in the Milky Way? How many double neutron stars are there in close binaries? And what is the expected merging rate? Among the key processes for stellar nucleosynthesis, the sources of neutrons represent a longstanding and debated open problem [22, 23]. Neutron-captures (slow or rapid, i.e., the s or r process, respectively) were early recognized as the most important mechanism to produce the elements heavier than iron. The identification of the astrophysical sites where these processes may operate requires the accurate knowledge of the efficiency of the possible neutron sources. Various reactions have been identified as promising neutron sources. Among them $^{13}$C$(\alpha,n)^{16}$O and $^{22}$Ne$(\alpha,n)^{25}$Mg represent the most favored candidates. This is because they operate from relatively low temperatures typical of He burning (100 - 300MK) and because $^{13}$C and $^{22}$Ne are relatively abundant nuclei in stellar interiors. The $^{13}$C$(\alpha,n)^{16}$O reaction operates in the He-burning shell of low-mass (less than 4 solar masses) AGB stars and it is the neutron source reaction that allows the creation of the
bulk of the s-process elements such as Sr, Zr and the light rare earth elements in the Universe. The $^{22}\text{Ne}(\alpha,\text{n})^{25}\text{Mg}$ reaction operates in the He-burning shell of high-mass (more than 4 solar masses) AGB stars and during the core-He burning and the shell-C burning of massive stars (more than 10 solar masses). Underground experiments with LUNA MV will allow us to gain a full understanding of these two reactions through the direct measurement of their cross sections in the energy range of astrophysical interest. The LUNA-MV facility will be installed at the north side of Hall B and will consist of an accelerator room with concrete walls and a further building hosting the control room and technical facilities including the cooling system, the electric power center, etc. (Figure 6.3.5). The concrete walls and ceiling (thickness of 80 cm) of the accelerator room serve as neutron shielding. Considering the worst case scenario for the operation of the LUNA MV facility of maximum neutron production rate of $R_n = 2 \cdot 10^3 \text{ s}^{-1}$ with an energy $E_n = 5.6 \text{ MeV}$, validated Monte Carlo simulations determined a maximum neutron flux outside the shielding of $\phi_{\text{max}} = 5.70 \cdot 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$. This value is a factor of 5 lower than $\phi_{\text{LNGS}} = 3 \cdot 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$, the reference neutron background at LNGS. In addition, the energy distribution of the neutrons produced by LUNA MV just outside the shielding is very similar to that of the natural background at LNGS.

The LUNA MV accelerator is an Inline Cockcroft Walton accelerator designed and constructed by High Voltage Engineering Europe (HVEE). The machine will cover a Terminal Voltage (TV) range from 0.2 to 3.5 MV and will deliver ion beams of $\text{H}^+$, $^4\text{He}^+$, $^{12}\text{C}^+$ and $^{12}\text{C}^{++}$ in the energy range from 0.350 to 7 MeV into two different beam lines via a $35^\circ$ switching analyzing magnet (see Figure 6.3.5). The two independent targets will be located at 2 m distance from the analyzing magnet. Details of the characteristics of the machine can be found in Table 6.3.5.

The delivery of accelerator to LNGS is scheduled for the first months of 2019. The six months installation and commissioning phase at LNGS will start directly after installation and is under the responsibility of HVEE. Data taking for physics experiments is envisaged to start in summer 2019. The scientific life of the new facility will be of 25-30 just considering the possible experiments in nuclear astrophysics and can go well beyond if including applications to other fields even outside the fundamental research frame. A proposal for the first five years of activity at LUNA-MV has been approved by the LNGS Scientific Committee. Such program includes the direct measurement of the cross section of the $^{12}\text{C}^++^{12}\text{C}$, $^{13}\text{C}(\alpha,\text{n})$ and $^{22}\text{Ne}(\alpha,\text{n})$ reactions and a renewed study of the $^{14}\text{N}(p,\gamma)$ at energies higher than those previously explored at LUNA400 (this experiment will also be partially used in the LUNA MV commissioning phase). In a successive phase, $^{12}\text{C}(\alpha,\gamma)$ should also be studied with a dedicated set-up.

6.3.4 Expected improvements in comparison with literature

The core of the LUNA mission is to provide solutions or clear steps forward in the knowledge of nuclear processes relevant in astrophysical scenarios. The scientific cases selected for experiments at LUNA400 and LUNA MV will follow this basic criterion. For instance, a very recent experiment carried out with the so-called Trojan Horse Method, claimed the existence of several resonances in $^{12}\text{C}^++^{12}\text{C}$ in the so far un-explored region at $E_{\text{cm}}$ 1- 2.1 MeV [90]. This observation would imply a significant increase in the reaction rate and a corresponding lowering of the mass limit of star for which carbon-burning can ignite. An independent verification of such result is definitively needed and LUNA-MV is the sole
laboratory in the world where a low-energy direct experiment can be performed. Actually, the $^{12}\text{C}^+^{12}\text{C}$ experiment will be the main goal/task in the first years of life of the new underground facility.

6.3.5 International competition

The LUNA achievements have motivated the proposals for two similar facilities currently under construction in the Republic of China (JUNA project) and in the United States (CASPAR project). In the first case, intense p and He beams (project target: 10 mA) will be accelerated up to 400 kV (deployment within 2019) while the American project is based on a refurbished 1 MV accelerator which has been put in operation in 2018 and that can deliver p and He beams with intensities in the range of 0.1 mA. The scientific cases of both facilities are partially overlapping with the LUNA-MV program in particular for the processes which can be studied without a carbon beam (available at LUNA MV only). A shallow underground accelerator has been also installed in Dresden (Felsenkeller project): in this case, the background level is much less favorable, however, the availability of a carbon beam must be underlined. In short: LUNA is no more the sole underground nuclear astrophysics facility and the next decades will develop in a framework of strong international competition.

<table>
<thead>
<tr>
<th>Expected ion beam currents transported through an aperture (length 40 mm, diameter 5 mm) located at the target position</th>
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<tr>
<td><strong>Ion</strong></td>
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<tr>
<td>$^1\text{H}^+$</td>
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<td>$^4\text{He}^+$</td>
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<td>$^{12}\text{C}^+$</td>
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<td>$^{12}\text{C}^{2+}$</td>
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<th>Other ion beam parameters</th>
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<tr>
<td>Beam current stability over 1 h</td>
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<td>Beam energy stability over 1 h, whichever higher</td>
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<td>Beam energy reproducibility, whichever higher</td>
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<tr>
<th>Operational details</th>
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<tr>
<td>Ion species change-over duration</td>
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<tr>
<td>Intervention-free operation</td>
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<td>Interruption time after maximum intervention-free operation</td>
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<tr>
<td>Servicing interval</td>
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<tr>
<td>Annual operation capabilities</td>
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Table 1: Main features of the LUNA-MV accelerator
Figure 3: Top panel: layout of the LUNA-MV installation with the 3.5 MV accelerator in Hall B at LNGS. Bottom panel: schematic of the LUNA-MV accelerator plus a beam line (tendered to HVEE) and a picture of LUNA-MV ready at the manufacturer factory (March 2018)
6.4 n-TOF

6.4.1 Experimental techniques

The n_TOF facility was proposed and built at CERN with the aim of addressing the needs of new data of interest for Nuclear Astrophysics, as well as for basic Nuclear Physics and for technological applications [3]. Neutrons are produced by spallation of a pulsed proton beam of 20 GeV/c momentum from the Proton Synchrotron (PS) impinging on a water-cooled Pb target. The high peak current of the PS proton beam, combined with the high energy, results in a very intense neutron source, and in a very wide energy spectrum. The use of demineralized or borated water ensures additional moderation of the neutron energy, leading to an almost isolethargic spectrum. For the first thirteen years of operation, only one neutron beam line, in the horizontal direction, was available, with the experimental area (EAR1) located at 185 m distance from the spallation target. In this area, the neutron beam is characterized by an instantaneous intensity of $10^6$ neutrons/bunch, an energy spectrum extending over almost eleven orders of magnitude, from 25 meV to 1 GeV, and a high energy resolution ($\Delta E/E < 10^{-3}$ in most of the energy range). The combination of the high luminosity and resolution makes the neutron beam in EAR1 very convenient for measurements of capture cross sections of interest for Nuclear Astrophysics, involving in particular unstable s process branching point isotopes.

In 2014, a second beam line in the vertical direction was completed at n_TOF [91]. The corresponding experimental area (EAR2) is located at 20 m distance from the spallation target. Compared with EAR1, the neutron beam in the new area has a much higher intensity ($> 10^7$ neutrons/bunch), at the expenses of a worse energy resolution and slightly smaller energy range. The two experimental areas are somewhat complementary: while the characteristics of the neutron beam in EAR1 are ideal for high resolution measurements of neutron capture reactions on stable or long-lived radioactive isotopes ($t_{1/2} > 100$ y), the much higher flux in EAR2 allows one to perform measurements on radioisotopes with short half-life, on samples available in small (sub-mg) mass, on reactions with low cross section, or on all of these at the same time. In fact, for radioactive isotopes the combination of the higher flux and shorter time-of-flight results in an increase of the signal-to-background ratio of more than two orders of magnitude, relative to EAR1, when considering the background related to the radioactivity of the sample. As a consequence, the neutron beam in EAR2 allows challenging measurements on isotopes with half-life as short as a few months. This was indeed the case for the measurement of neutron-induced reactions on $^7$Be of interest for BBN [12, 28].

The extremely high luminosity of the neutron beam in EAR2 is particularly convenient for measurements of neutron-induced fission cross sections on short-lived actinides. Such measurements are of key importance for the correct modelling of the fission recycling in r process nucleosynthesis.

Apart from the unique features of the neutron beams in the two experimental areas, research in Nuclear Astrophysics at n_TOF can benefit from state of the art detection and acquisition systems [4]. In measurements of neutron capture reactions, a large step forward in the accuracy of the results has resulted from the development of new $\gamma$-ray detectors characterized by a very low neutron sensitivity and from a specifically designed DAQ [4]. For fission measurements, a big improvement in the quality of the data has resulted from the use of Micromegas detectors and of ultra-fast Parallel Plate Avalanche Counters specifically designed for n_TOF.
6.4.2 Current Nuclear Astrophysics measurements

All the elements heavier than iron are synthesized by neutron induced reactions in the s process or in the r process. Both, the s and r process, are based on neutron capture reactions. In particular, for the s process there is a direct correlation between the neutron capture cross section, $\sigma(n,\gamma)$ and the observed abundance of a given isotope. This correlation makes it necessary to obtain neutron capture cross section data of all isotopes along the valley of $\beta$-stability, a program which has been going on since the early days of nuclear astrophysics.

Recently, this classic picture just described has been enriched by the enormous progress made by astronomical observations as well as by important developments in understanding and modeling stellar evolution. In particular, not only the need for neutron capture cross sections is enhanced by these recent developments, but the necessity of high accuracy is evident. The direct impact of accurate neutron capture cross sections on the nucleosynthesis modeling can be tested with measurements of elemental abundances in low-metallicity stars as well as in isotopic abundances measured for SiC grains imbedded in meteoritic material.

Particularly unique features of s process nucleosynthesis are branchings in the reaction path. Since typical neutron capture times are of the order of one year, the majority of unstable isotopes encountered by the neutron capture chain decays so fast that neutron capture becomes negligible. A number of isotopes, however, exhibit half lives comparable with the neutron capture time. The resulting competition gives rise to a branching of the reaction path, a local phenomenon that involves usually not more than eight isotopes before the branching is closed and the capture path continues as a single reaction chain. Detailed analyses of such branchings are so fascinating because the evolving abundance patterns reflect the physical conditions at the stellar site of the s process. In the simplest case, this is the stellar neutron flux but there are branchings that are strongly determined by temperature, or even by the convective motions in the deep stellar interior. Obviously, this type of information represents stringent tests for stellar models of the AGB phase, which is known to be the stage when the s process operates. A prominent example of a branching point is $^{151}$Sm, which determines the reaction flow towards the s-only isotope $^{152}$Gd. The neutron capture cross section of $^{151}$Sm ($t_{1/2} = 93$ years) has been successfully measured at n_TOF with an accuracy of better than 5% \cite{11}. \cite{12}. Such measurements are difficult because the radioactivity of the sample may cause excessive backgrounds in the detectors or may be unacceptable because of standard safety limits. Both problems suggest that sufficiently sensitive techniques are required, which can tolerate the use of extremely small samples.

Since the s process component can be reliably determined on the basis of accurate $(n,\gamma)$ cross sections, the r process counterpart is obtained by the difference with the observed abundances

$$N_{r-process} = N_{star} - N_{s-process}$$

Recent spectral analyses of very old stars have shown that they contain essentially only r process material and that the abundances of all elements heavier than Ba scale precisely as in the solar r process pattern. Below Ba this perfect agreement appears strongly disturbed. This could either indicate the operation of two independent r processes or could
simply be due to uncertain s process abundances, since the cross sections in this mass region exhibit large uncertainties.

A huge step forward in this matter has resulted from the recent multi-messenger observation of a Neutron Star Merger (NSM) in August 2017. The simultaneous detection of gravitation waves, gamma-ray burst and electromagnetic radiation in the optical and near-optical range has unequivocally demonstrated that NSM are an important, if not the most important, site for r process nucleosynthesis.

6.4.3 Focus on relevant measurements

Based on these considerations, an experimental program to be performed at n_TOF has been defined. This program includes capture cross section measurements on the stable isotopes of Fe, Ni, Zn, and Se [41, 55, 62]. These elements are produced by s-process nucleosynthesis in massive stars. In a number of cases, the respective neutron capture cross sections act as bottle-necks in the s-process reaction flow, thus strongly affecting the production of the elements with higher masses. In addition to the stable isotopes, measurements on some radioactive targets in the same mass region can be performed at n_TOF. Examples of branchings related to the weak s process are $^{63}$Ni ($t_{1/2} = 100$ years) [56] and $^{76}$Se ($t_{1/2} = 6.3 \times 10^4$ years).

The second group of isotopes of interest consists of the stable isotopes of Mo, Ru, and Pd. Their neutron capture cross sections are required for two main objectives: for the interpretation of the isotopic patterns in pre-solar SiC grains and for the reliable determination of the r-process abundances in the critical mass region between Zr and Ba. SiC grains are found in meteorites and originate from circumstellar clouds of AGB stars, which are highly enriched in fresh s-process material produced by these stars. These grains are so refractory that they survived the high temperatures during the collapse of the proto-solar cloud. Hence, their composition represents the most direct information on the s-process efficiency of individual stars, an important constraint for current s-process models.

The third group of measurements concerns unstable branch point isotopes related to the main s-process component. So far, the feasibility of such measurements has been demonstrated at n_TOF at the examples of $^{151}$Sm ($t_{1/2} = 93$ yr) and $^{93}$Zr ($t_{1/2} = 1.5 \times 10^6$ yr) [86] and should be extended to cases like $^{134}$Cs ($t_{1/2} = 2.06$ yr). Other unstable isotopes which could be considered for new measurements are: $^{85}$Kr, $^{107}$Pd, $^{135}$Cs and $^{185}$W.

The $^{13}$C($\alpha$,n)$^{16}$O reaction is the main neutron source in low mass AGB stars. When the direct approach to the study of ($\alpha$,n) reactions is particularly difficult, indirect or inverse reactions are considered as a valid method for constraining the reaction cross sections of astrophysical interest. Therefore, the challenging $^{13}$C($\alpha$,n)$^{16}$O measurement can benefit from experimental information from the time-reversed reaction $^{16}$O(n,\alpha)$^{13}$C, which can provide information on the orbital angular momenta of the excited states.

Neutron induced reactions on light nuclei may be of key importance for heavy element abundances produced in the s-process, as they may act as neutron poison. The most important poison for the s process are the $^{14}$N(n,p)$^{14}$C and the $^{26}$Al(n,p)$^{26}$Mg reactions. The first works in radiative conditions, when neutrons are released by the $^{13}$C($\alpha$,n)$^{16}$O reactions, and it is able to shape the whole s-process distributions. The latter operates in a convective environment during the neutron burst provided by the $^{22}$Ne($\alpha$,n)$^{25}$Mg reaction and modifies isotopic compositions close to branchings along the s process path.
6.4.4 Neutron cross sections for Big Bang Nucleosynthesis

Nuclear reactions responsible for the $^7$Be creation and destruction during Big Bang Nucleosynthesis (BBN) play the key role in the determination of the resulting primordial abundance of $^7$Li. Current standard BBN models predict a $^7$Li abundance which is a factor of 2-3 larger than what can be determined by astronomical observations. A neutron channel which could enhance the destruction rate of $^7$Be during BBN has been the subject of recent research activities at n_TOF.

The $^7$Be(n,α)$^4$He reaction has been measured for the first time in a wide neutron energy range [12]. A second reaction channel, the $^7$Be(n,p)$^7$Li has been explored [28], again extending the reaction cross section data to a wider range. The estimate of the $^7$Be destruction rate based on the new results yields a decrease of the predicted cosmological Lithium abundance of 10%, insufficient to provide a viable solution to the cosmological lithium problem. The two n_TOF measurements of (n,α) and (n,p) cross sections on $^7$Be finally ruled out neutron-induced reactions as a potential explanation of the cosmological lithium problem, leaving all alternative physics and astronomical scenarios still open.

6.4.5 Future Nuclear Astrophysics measurements

In the scenario of NSM, the large number of free neutrons per seed nuclei (of the order of a few hundred) leads to the production of heavy fissioning nuclei. As a consequence, neutron-induced fission reactions and, to a lesser extent, spontaneous fission play a fundamental role in the process, by recycling matter during neutron irradiation. Such process, referred to as fission recycling has an important effect on shaping the abundance distribution of r-nuclei in the mass region between A=110 and 170, as well as in determining the residual production of heavy nuclei, in particular Pb, Bi, Th and U. Finally, fission processes during r-process nucleosynthesis are expected to contribute to the heating of the material, due to the large energy released (the so-called KILONOVA event).

The effect of fission recycling depends on the fission probabilities of a large number of, mostly neutron-rich, nuclei. For the vast majority of these nuclei one can only rely on model prediction, which at presently are highly uncertain. Various models have been developed and are currently available, but at the present the prediction power of these models is still highly unsatisfactory. As an example, a comparison of the fission cross section estimated on the basis of these nuclear models shows discrepancies of up to a factor of ten relative to experimental cross sections, and it is reasonable to expect that the predictive power gets much worse for exotic nuclei. More work is therefore necessary to improve the situation towards more coherent and reliable fission models. To this end, a great help could come from new experimental data on actinides that have not been measured so far, or whose experimental cross section is affected by a large uncertainty. In this respect, high-luminosity neutron beams that have just become available or will come on line in the next few years will certainly offer the unique opportunity to collect precious data on short-lived actinides of interest for Nuclear Astrophysics. This is the case, in particular, of the high-flux experimental area EAR2 of the n_TOF facility at CERN.
6.4.6 Expected improvements in comparison with literature

In all cases discussed above, the main problem is related to the large uncertainty in the cross section data, that often represent the main limitation towards the refinement of theoretical models of nucleosynthesis and stellar evolution. The uncertainty in the nuclear input in turn reflects the lack of reliable experimental data. In some cases, measurements have been performed long time ago, with inadequate detector systems. As an example, neutron capture reactions have been measured in the past with detectors affected by a non-negligible neutron sensitivity, resulting in a large background and, consequently, in unrecognized systematic errors. For radioactive isotopes, the natural radioactivity of the sample represents another important source of background in capture measurements, leading to poor quality results. In fission measurements, the strong background related to the α-activity of the sample has often hindered the possibility to obtain accurate data, or even made the measurement impossible. Finally, the small amount of sample material available for some isotopes has made neutron measurements difficult, or has led to highly uncertain results. All these limitations have been mostly overcome at n_TOF thanks on the one hand to the high luminosity of the neutron beam, in particular in the second experimental area, and on the other hand to the optimization of the detection systems. Another improvement is related to the high resolution of the neutron beam in the first experimental area, which allows one to better identify and characterize resonances in the cross section. Finally, the wide energy range of the n_TOF neutron beam, extending over 10 orders of magnitude, allows to cover in a single measurement the entire energy region of interest for Nuclear Astrophysics, for a wide range of stellar temperatures, and results in a considerable reduction of normalization problems. All these features are expected to lead to sizable improvements over previous results, in terms of accuracy, resolution and energy range covered. Most importantly, several measurements that could not be performed in the past have now become feasible, so that data can be collected for the first time ever.

6.4.7 International competition

While a few high-flux activation facilities are now becoming available (such as SARAF in Israel, of the future FRANZ facility in Germany), n_TOF is predicted to continue playing a fundamental role for the determination of energy-differential cross sections in the mid-term future (the next ten years), as even new facilities currently under construction (such as NFS in GANIL, France) will not be able to meet the unique combination of high luminosity, wide energy range, high resolution and low background that characterizes the n_TOF neutron beams. These features are fundamental to drastically improve the accuracy on the cross section for a variety of neutron-induced reactions of interest for Nuclear Astrophysics. Most importantly, they will allow to perform challenging new measurements, not possible up to now, for example on short-lived radioactive isotopes. To this end, the possibility to irradiate samples produced by implantation of radioactive beams could result in a number of unique measurements. The viability of this technique has just been successfully demonstrated at CERN in the measurement of the $^7$Be($n$,p)$^7$Li reaction of interest for BBN, with a $^7$Be sample produced at ISOLDE. In the landscape of the present and future neutron facilities worldwide, the ISOLDE/n_TOF combination represents a unicum that will hardly be met in other laboratories.
6.5 ALICE

The measurements of astrophysical interest that can be carried out by the ALICE experiment [1] using proton–proton and heavy-ion collisions are mainly those related to the production of light nuclei and hypernuclei on the one hand, and to the interactions between pairs of baryons (two protons, a proton and a hyperon, and two hyperons) on the other hand. These measurements can provide insight on the production of light nuclei and hypernuclei in the early Universe and in cosmic-ray interactions, also in connection with dark matter searches, and on the equation of state of compact stellar objects with high baryon density cores, either non-strange or strange.

6.5.1 Experimental techniques

The production of protons and stable light nuclei is measured in ALICE in the central rapidity region using track reconstruction and heavy-particle identification through ionisation energy loss in the Time Projection Chamber gas and time-of-flight from the interaction point to the Time Of Flight detector. The production of hyperons and hypernuclei is measured by reconstructing their weak-decay secondary vertices in the Time Projection Chamber and in the Inner Tracking System.

6.5.2 Current Nuclear Astrophysics measurements

Baryon–baryon interactions via femtoscopic measurements

The study of the hyperon-nucleon and hyperon-nucleon-nucleon interaction has become more and more crucial in recent years due to its connection to the modelling of astrophysical objects like neutron stars. In the inner core of these objects the appearance of hyperons is a probable scenario, because their formation is often energetically favoured in comparison with a purely nucleonic matter composition. However, the appearance of these additional degrees of freedom leads to a softening of the matter equation of state (EOS) that makes the EOS incompatible with the observation of two neutron stars of two solar masses [10, 29]. This leads to the ‘hyperon puzzle’ [14]. Many attempts were made to solve this puzzle, e.g. by introducing three-body forces leading to an additional repulsion that can counterbalance the large gravitational pressure and finally allow for large star masses. To constrain the parameter space of such models a detailed knowledge of the hyperon-nucleon interaction (HNI) and of the hyperon-nucleon-nucleon interaction is mandatory, including Λ, Σ and Ξ states.

The hyperon-nucleon (YN) interaction can be studied using femtoscopy, i.e. the correlation function of particle pairs at low relative momentum, in particular in small colliding systems as pp, where the emitting source is well constrained (e.g. by precise proton-proton femtoscopy). A first ALICE measurement [5] demonstrates that the p-Λ and Λ-Λ correlation functions constrain the phase space spanned by the effective range and scattering length of the strong interaction. The results for the Λ–Λ case are summarized in Fig. 6.5.2 (left).

Production of hypernuclei

A hypernucleus is a nucleus that contains at least a hyperon in addition to protons and neutrons. The lifetime of a hypernucleus depends on the strength of the hyperon-nucleon
(YN) interaction. The study of this interaction is relevant for nuclear physics and nuclear astrophysics. For example, it plays a key role in understanding the structure of neutron stars. Depending on the strength of the YN interaction, the collapsed stellar core could consist of hyperons, strange quark matter, or a kaonic condensate. The Pb-Pb data set collected by ALICE in the LHC Run-1 and Run-2 already allowed for a first yield and lifetime measurements of hypertriton $^3\Lambda H$ and anti-hypertriton [7]. The detection of heavier (anti)-hypernuclei will be possible with future Run-3 and Run-4 samples.

**Production of light nuclei and anti-nuclei**

The measurement of light nuclei production in pp collisions at ultra-relativistic energies has an impact on cosmology. Big-bang nucleosynthesis is the dominant natural source of deuterons and, in the absence of baryogenesis, one could assume that the same holds for anti-deuterons. These anti-nuclei and even heavier anti-nuclei can also be produced in pp and pA collisions in interstellar space, representing a background source in the searches for segregated primordial antimatter and dark matter [35]. However, experimental information on anti-d and anti-$^3\Lambda H$ production is scarce and, for the most part, limited to AA or pA collisions. ALICE has recently measured the production of nuclei and anti-nuclei in pp collisions at different energies, including for the first time anti-nuclei heavier than anti-deuteron [6]. The ALICE results show an increasing trend in the (anti-)d/(anti-)p ratio with charged particle multiplicity. Furthermore the values reported in central AA collisions are in agreement with a thermal model description while the highest d/p ratio measured in pp collisions by ALICE is about half the thermal model value; therefore, a thermal-statistical description is disfavored in pp collisions at these low average charged particle multiplicities. In addition the ALICE data are well described by QCD-inspired event generators when a coalescence-based afterburner that also takes into account the momentum correlations between nucleons is included.
6.5.3 Future Nuclear Astrophysics measurements

Baryon–baryon interactions via femtoscopic measurements

The data samples of pp collisions that will be collected during LHC Run-2 and Run-3 will be larger by factor 10 and 100, respectively, with respect to that used in [5]. These will enable to constraint the phase space spanned by the effective range and scattering length of the Λ-p and Λ-Λ interaction and to extend the measurement also to Σ, Ξ and Ω hyperons and thus further constrain the Hyperon-Nucleon interaction.

Production of hypernuclei

The data sample of Pb–Pb collisions that will be collected during LHC Run-3 and Run-4 will be larger by a factor 100 with respect to that of the ongoing Run-2. This sample will enable very precise measurements of the production of $^4_ΛH$ and first ever experimental measurement of $^3_ΛH$ and $^4_ΛHe$ via their weak decays, see Fig. 6.5.2 (right).
6.6 GAMMA

6.6.1 Experimental techniques

The GAMMA experiment carries out nuclear structure studies via gamma spectroscopy measurements. The activity is based on the use of multi-detector arrays at facilities delivering stable (e.g., LNL Legnaro, GANIL,...) and radioactive (e.g., ISOLDE, GSI/FAIR, RIKEN, ...) ion beams, and intense neutron beams (e.g., ILL-Grenoble), in the framework of international collaborations. A well defined research program is also foreseen at SPES. The experimental setup always involves the use of high resolution Ge detector arrays, such as the state-of-the-art project AGATA (Advanced Gamma Tracking Array) \[9\], and the GALILEO array at LNL. The gamma spectrometers are most often coupled to complementary detectors, boosting their sensitivity to weak reaction channels, hard to reach with standard gamma spectroscopy techniques. Notable examples are arrays made of large volume scintillators for high-energy gamma-rays (e.g., the Italian array HECTOR+ of 8 LaBr$_3$ detectors and the international project PARIS \[59\]), arrays of highly segmented Si detectors for charged particle detection (e.g., the SPIDER \[47\] detector and TRACE/MUGAST array \[34\]), neutron detectors (e.g., the NEDA array \[49\]), as well as magnetic spectrometers (e.g., PRISMA at LNL and VAMOS at GANIL).

Such complex setups will allow to investigate, with unprecedented sensitivity, the structure of astrophysically relevant nuclei. For examples, it will be possible to measure branching ratios for gamma emission from unbound (resonance) states (via particle-gamma coincidence techniques), lifetimes of narrow, near threshold resonances (employing Doppler Shift Attenuation techniques down to the femtoseconds time scale), as well as angular distributions and the electric/magnetic character of the radiation, by using continuous angle variable.

6.6.2 Future Nuclear Astrophysics measurements

Key inputs to define reaction rates in stars are i) nuclear structure properties of light nuclei relevant for thermonuclear fusion reactions, ii) shapes/deformation and resonance (pygmy) excitation modes of exotic species lying along or in the vicinity of the s- and r-process paths, as well as iii) neutron-capture cross sections and vi) beta-decay half-lives and neutron emission probabilities. As briefly described below, in each case, a significant step forward is expected in the coming years, taking advantage of the combined availability of the multi-detector setups, currently being developed within the GAMMA community, and high intensity stable and radioactive ion beams.

i) Light nuclei

The structure of light nuclei of Be, Li, C, O, N, ... plays a key role in thermonuclear fusion reactions in stellar objects. In this context, the measurement of electromagnetic decays from unbound states in neutron-rich systems would represent a breakthrough. At present, such information is very scarce, owing to gamma-decay branchings of the order of $10^{-4}$-$10^{-3}$ and lower. Of paramount importance are, in particular, near threshold resonances (such as the famous "Hoyle" state in $^{12}$C), most often exhibiting a pronounced cluster structure which directly impacts reaction rates \[68, 69\].

In the near future, fusion reactions with intense $^6,^7$Li and $^{14}$C beams on $^9$Be, $^{12,13}$C, $^6,^7$Li and $^{10}$B targets are planned to be employed to populate unbound states in $^{13}$B, $^{15}$C,
O and $^{16}$N, after a single evaporated proton, directly feeding the resonance state from which the gamma decay will be measured.

Astrophysically important proton-rich nuclei involved in the rp-process nucleosynthesis will also be explored at SPES with the available $^{25,26}$Al using indirect approaches, such as ($^3$He,d) or (d,n) reactions. Knowledge of resonant states in $^{26}$Si and their gamma-decay branch are key to constraint the reaction rates of the $^{25}$Al(p,gamma)$^{26}$Si reaction that are required to understand the synthesis of $^{26}$Al in explosive hydrogen burning. Thick cryogenic targets will allow a breakthrough in these type of studies.

ii) nuclear shapes, deformation and resonance (pygmy) excitation modes

The evolution of nuclear shapes along isotopic chains, including sudden dramatic changes from spherical to deformed systems (as seen in neutron-rich nuclei with $Z = 36-40$ near $N = 60$ [24, 50, 87]), leads to significant changes in beta-decay half lives and proton emission probabilities, with strong impact on the r-process path. **In the near future,** Coulomb excitation and cluster transfer [16] reactions with intense exotic beams (in particular neutron rich Kr, Rb, Y and Sr from SPES) will be instrumental for reaching a detailed picture of how nuclear shells evolve away from stability.

Concerning collective excitations, the presence of dipole strength at low excitation energy has been often associated to the oscillation of a neutron skin outside the proton-neutron core: the Pygmy Dipole Resonance mode ([17, 81] and reference therein). Its strength is expected to be more pronounced in nuclei far from stability and to play a significant role in the r-process nucleosynthesis [42, 43, 75] (see Fig. 5. Moreover, its properties can be used to constrain the equation of state of neutron rich matter and the radius of low mass neutron stars. At present, scattered information is available for exotic systems of O, Ni and Sn, however, future, extended, systematic investigations are planned with high intensity exotic beams (e.g. along the Sr isotopic chain at SPES) [54].

Figure 5: Left: The E1 pygmy dipole strength measured in few nuclei, as a function of the neutron excess [81]. Right: Predicted impact of the pygmy mode (open triangles GDR+PR) on element abundances in the solar system (full symboles) [42].
iii) \((n,\gamma)\) cross sections

For several astrophysically relevant isotopes, our knowledge of \((n,\gamma)\) reaction cross sections is purely theoretical. Some examples on the r-process side are \(^{79}\text{Se},^{81,85}\text{Kr},^{86}\text{Rb},^{65}\text{Zn},^{121}\text{Sn}\). There are also many radioactive nuclei located along or close to the s-process path for which there is neither a theoretical approach nor experimental data. Notable examples are \(^{64}\text{Cu},^{108}\text{Ag},^{109}\text{Pd},\) and \(^{123}\text{Sn}\).

In the near future, neutron capture cross sections for the above mentioned isotopes could be accessed by the measurement of partial cross sections for the population of the final states of the residues formed in the light-ion direct reactions. If the nuclei of interest are exotic, these quantities would be extracted directly via the measurement of light-ion direct reaction in inverse kinematics, performed onto a \(\text{CD}_2\) target. In the case of stable nuclei, indirect methods could also be used, such as the surrogate method [36] in which the relevant compound nucleus reaction cross section of interest is deduced via a \((d,p)\) reaction study.

iv) beta-decay half-lives and neutron emission probabilities

On the neutron rich side, beta decays, changing neutrons into protons, deviate the r-process path towards heavier species, and their rates define the possible occurrence of successive neutron capture. In this context, key quantities are beta-decay rates, existence of long-living isomeric states and competition with other decay modes, in particular with beta-delayed neutron emission. Such crucial information is fully available for a very limited number of r-process nuclei. Particularly relevant is the region of poorly known neutron rich Ge, As and Se nuclei, which are believed to be responsible for the overproduction of Sr, Y and Zr registered in Ultra-Metal Poor stars.

In the near future, half-lives measurements and the evaluation of probabilities for delayed neutron emission are planned to be pursued at SPES, using the beta-Decay Station setup equipped with plastic and HPGe detectors. Delayed neutron emission measurements would be performed both by studying the internal deexcitation of the successor, as well as by using dedicated setups.

6.6.3 International competition

The competitiveness of the astrophysically relevant nuclear structure studies carried out by the GAMMA collaboration resides in the power of the detection setup (e.g., AGATA, GALILEO and their ancillaries), and in the availability of high intensity stable/radioactive ion beams in Europe, in particular. This makes possible a top class research program in direct competition with similar sophisticated setups, as for example the state-of-the-art gamma spectrometer GRETA [57], currently being built in USA.
6.7 PANDORA

The investigation of nuclear phenomena like fusion reactions, or radioactive decays for astrophysical purposes, has become more and more interesting in the last decades: as a matter of fact, not yet solved issues on stellar and primordial nucleosynthesis or neutrino production require precise reaction rate or radionuclides lifetime measurements.

6.7.1 Experimental techniques

The basic idea of PANDORA [61] (Plasmas for Astrophysics Nuclear Decays Observation and Radiation for Archaeometry) is that compact and flexible magnetic plasma traps (plasmas density: \( n_e \simeq 10^{11} - 10^{14} \text{cm}^{-3} \), temperature: \( T_e \simeq 0.1 - 30 \text{keV} \)) are the place where measuring, for the first time, nuclear \( \beta \)-decay rates in stellar-like conditions. This is especially true for radionuclides involved in nuclear-astrophysics processes and cosmology (BBN, s-process, Cosmo-Chronometers, Early Solar System formation). The decay rates can be measured as a function of the charge state distribution of the in-plasma ions, and eventually of the plasma density and temperature. Experiments performed at GSI on highly-charged ions have already demonstrated that the Electron Capture (EC) decay probability can be dramatically modified by the atomic electron configuration. In H-like and He-like \(^{140}\text{Pr}^{57+}\) to \(^{140}\text{Pr}^{58+}\) ions, the EC decay rate increased by a factor of 1.5.

6.7.2 Current Nuclear Astrophysics measurements

PANDORA is now in its feasibility study phase, which started in 2017, and it is financed by CSN5. Two issues are preparatory to Nuclear Astrophysics experiments: how to measure in-plasma ions charge states distribution (CSD) (thereby correlating CSD to lifetimes)? How to optimize the handling and the injection of rare isotopes inside the magneto-plasma?

Concerning the first issue, a multi-diagnostics characterization of the plasma started at LNS and in other partner laboratories in 2017. The setup includes optical and X-ray spectroscopy, microwave interferopolarimetry, etc. In addition, according to a INFN-INAF MoU approved in August 2017, the powerful spectropolarimeter SARG (Spettrometro Alta Risoluzione Galileo, \( R = 160.000 \) in the range: 370-900 nm) was moved from the Telescopio Nazionale Galileo in Canary Islands to INFN-LNS, where it is currently being installed. Concerning the second issue, some radionuclides can be handled by conventional vaporization methods. For very short-living species, a Charge Breeding (CB) technique should be applied. As done in ISOL-like facilities such as ISOLDE, SPES and SPIRAL1, 1+ ions produced at the target can be then injected into a magnetically confined plasma and there in-flight captured. LNS-LNL synergies have permitted to already perform an experiment at LPSC-Grenoble, in late 2017, showing that CB is possible provided that the injection occurs after an ion RF-cooler system.

6.7.3 Future Nuclear Astrophysics measurements

Among the various isotopes, some have been selected for their relevance in Nuclear Astrophysics. \(^7\text{Be}\) decay is one of these, since beryllium is the responsible of the primordial
abundance of $^7\text{Li}$. The BBN nucleosynthesis of $^7\text{Be}$ takes place in a quite peculiar plasma environment. As a consequence, any modification of the decay probability could significantly affect the BBN network, deeply modifying the whole scenario and thus providing new clues about the lithium problem. Another very interesting case is the one of $^{85}\text{Kr}$, that is a crucial branching point of the s-process that deeply affects the abundance of Sr and Rb isotopes in stars. Other relevant measurements can be possible for $^{176}\text{Lu}$ and the pairs $^{187}\text{Re} - ^{187}\text{Os}$ and $^{87}\text{Sr} - ^{87}\text{Rb}$, which play a crucial role as cosmo-clocks. Lifetimes can be estimated by detecting the emitted $\gamma$-rays. Some of the produced isotopes do not emit $\gamma$-rays. However, alternative ways to estimate the number of decay products can be found, such as their extraction from the plasma and their implantation on special targets that can be then post-processed by XRF techniques to estimate the abundances. More details on the proposed radionuclides are listed in the following:

- $^7\text{Be} \rightarrow T_{1/2} = 53d$. This decay is involved in BBN. The decay can be tagged by $^7\text{Li}$ $\gamma$-rays emission at 477.6 keV.
- $^{85}\text{Kr} \rightarrow T_{1/2} = 10.76y$. Involved in s-processes. The decay can be tagged by $\gamma$-rays emission at 514 keV.
- $^{176}\text{Lu} \rightarrow T_{1/2} = 38Gy$. Used as Cosmo-Chronometer. The decay can be tagged by $\gamma$-rays emission at 202.88 and 307 keV
- $^{187}\text{Re} \rightarrow T_{1/2} = 50Gy$. Used as Cosmo-Chronometer. The decay does not produce $\gamma$-rays, but it can be tagged by looking at $^{187}\text{Os}$ eventually extracted from the plasma.
- $^{87}\text{Rb} \rightarrow T_{1/2} = 48Gy$. (Cosmo-Chronometers). The decay does not produce $\gamma$-rays, but it can be tagged by looking at $^{87}\text{Sr}$ eventually extracted from the plasma.

### 6.7.4 Expected improvements in comparison with literature

Nuclear decay lifetimes of radionuclides of astrophysical interest have never been measured in magnetized plasmas. The measurements that are planned in PANDORA will be competing/complementing the ones already performed on Storage Rings (SR) (see for instance [45]. The main advantage with respect to SR is that in PANDORA even long-lifetime isotopes can be studied, since the magnetoplasma can be tuned in a dynamical equilibrium (i.e. keeping constant the plasma density, temperature and charge state distribution) for days, or even weeks.

### 6.7.5 International competition

The interest for PANDORA in groups working worldwide in the field of ECR plasma traps is constantly growing. As a matter of fact, GANIL and LPSC-Grenoble (in France), Jyvaskyla University (in Finland) and the ATOMKI laboratory of the Hungarian Academy of Sciences (in this case, an official letter of interest has been endorsed) have already presented informal or even formal letters of intents for starting a scientific collaboration. As mentioned before, the measurements of some of the radionuclide lifetimes (e.g. $^7\text{Be}$) is now a topic of some storage ring facilities, such as the one in the design phase at HIE-ISOLDE.
6.8 SPES

The SPES radioactive ion beam facility, presently under construction at LNL, is based on the isotope separation on-line technique. A primary proton beam, provided by the driver accelerator, is used to induce nuclear reactions inside a thick target like silicon carbide or uranium carbide. The reaction products are extracted from the target by thermal processes due to the high temperature of the target-ion-source system. Once reached the source the reaction products are ionized ($1^+$) and extracted. After an isotopic selection the radioactive elements undergo a subsequent ionisation ($n^+$ charge state) by means of a charge breeder to be further re-accelerated by the LNL superconductive linear accelerator ALPI. Accelerated radioactive ions, both in the low energy branch (after isotopic selection) or in the high energy branch (after passing the linac), are then used for basic nuclear research and for nuclear physics based applications. The primary proton beam is delivered by a cyclotron accelerator with an energy of 40 MeV and a beam current of 200 $\mu$A. Isotopic selection is obtained by the High Resolution Magnetic Spectrometer (HRMS) coupled to a Beam Cooler (BC). To boost the charge state of the produced radioactive ions, and allow post acceleration by a newly designed Radio-Frequency Quadrupole (RFQ) coupled to the existing superconductive linear accelerator ALPI, an Electron Cyclotron Resonance (ECR) based charge breeder (CB) has been realized. To suppress contaminants introduced by the ECR a Medium Resolution Magnetic Spectrometer (MRMS) has been added to the beam line. The aim is to provide reaccelerated high intensity ($I= 10^7 - 10^9$ particle per second) mainly neutron-rich secondary beams at energies of about 10 MeV/A, an energy regime allowing to overcome the Coulomb barrier to all stable targets.

Main aim of the proposed research is the study of the reactions that are at the basis of the element formation in the universe. Heavy elements from iron up to uranium are produced by neutron captures by the so-called rapid (r) and slow (s) processes. The study of those neutron capture reactions, essential for a quantitative understanding of the element formation in the universe, is the main objective of the astrophysical research at SPES.

6.8.1 Experimental techniques

Since nuclei involved in such processes are generally short-living and a neutron target cannot be realized, such reaction studies have mainly to rely on indirect methods. The experimental techniques we propose to use are the Trojan Horse (THM) and the Surrogate Ratio (SRM) methods. The SRM uses a different (surrogate) reaction to produce the compound nucleus of interest which, by definite kinematical conditions, populates the same excited states [71, 72]. The method assumes that the formation of the compound nucleus can be accurately described by nuclear models. The decay of the compound nucleus, where different channels are competing with each other as a function of neutron energy, is the goal of the experimental investigation. The measured decay probabilities of the compound nucleus are then used to tune model parameters leading to the neutron-induced cross sections. Suitable reactions are exchange reactions with light nuclei, e.g. (d,p). In such a case a radioactive ion beam is directed onto a deuterium (d) gas target. During the particle exchange the neutron of the deuterium target is passed on to the projectile nucleus and the remaining proton is detected. The knowledge of the full kinematics of the proton allow to select the excitation energy level of the compound. Such excited compound nucleus will
then de-excite via $\gamma$-emission (capture), neutron emission (inelastic scattering) etc. The measurement of the $\gamma$ decay of the compound will allow to select the different channels. Another case of interest is the inelastic-scattering reaction of deuterons - denoted $(d,d')$ - where the deuteron is scattered leaving the heavy projectile in an excited state. Very important is the influence of the populated angular momentum and parity on the decay probabilities. In most cases the differences between the distributions populated by the surrogate and the desired neutron-induced reaction have to be taken into account through a normalization to a reference case (surrogate ratio method).

6.8.2 Future Nuclear Astrophysics measurements

i) S-process nucleosynthesis:

$^{85}$Kr(n,$\gamma$) reaction rate relevant for the study of the $^{85}$Kr branching point of the s-process. The neutron capture cross section on $^{85}$Kr, competing with the beta decay of this unstable isotope with $T_{1/2} \approx 11$ y, is sensitive to the neutron density in the environment of the AGB star where the s-process takes place.

$^{79}$Se(n,$\gamma$): Elements with masses equal or heavier than A=80 are supposed to be synthesized by the s-process operating in AGB stars, where two alternate burning shells, one of H and an inner of He, surrounds an inert degenerate CO core. The He inter-shell is periodically swept by convective instabilities induced by He-burning runaway where $^{12}$C is synthesized. The main neutron source for AGB stars of mass $M \leq 4$ solar masses and $T \approx 10^8$ K is the $^{13}$C($\alpha$,n)$^{16}$O reaction (main s-process component) with a neutron density of $N_n \leq 10^7$ cm$^{-3}$. In the case of more massive stars, the s process takes place during pre-supernova evolution, i.e. during convective core He-burning and convective C-shell burning. In this case also the neutron source $^{22}$Ne($\alpha$, n)$^{25}$Mg is activated at temperatures of $T \geq 3.5 \times 10^8$ K and neutron densities of the order of $N_n \geq 10^{10}$ cm$^{-3}$ can be reached. Different s-process patterns are expected depending on whether the first or the second neutron source reaction is more active. The knowledge of the neutron capture cross sections in such branching nuclei together with the observed element abundances allow to estimate the neutron density at the s-process site.

ii) R-process nucleosynthesis:

Final r-process abundances are sensitive to neutron capture cross sections during freeze-out. Examples of capture reactions to be investigated with the early phase SPES beams are: $^{81}$Ge(n,$\gamma$), $^{78,80}$Ga(n,$\gamma$), $^{129,131}$Sn(n,$\gamma$), $^{134}$Sb(n,$\gamma$), $^{132,134,136,138}$Te(n,$\gamma$), $^{137}$Xe(n,$\gamma$).

iii) Light nuclei Direct reactions with light beams from SPES:

Novae:

$^{18}$F(p,$\alpha$)$^{15}$O, $^{30}$P(p,$\gamma$)$^{31}$S, $^{25}$Al(p,$\gamma$)$^{26}$Si, $^{26}$Al(p,$\alpha$)$^{23}$Mg using THM

Xray-burst:

$^{14}$O($\alpha$,p)$^{17}$F, $^{18}$Ne($\alpha$,p)$^{21}$Na, $^{30}$S($\alpha$,p)$^{33}$Cl.

6.8.3 Expected improvements in comparison with literature

Most of the proposed reactions are based on beams not available at existing facilities with sufficient intensities.
6.8.4 International competition

Main competition in Europe is CERN-ISOLDE (CH). In the future FRIB (USA) and the upgrade of TRIUMF (Canada) will provide more intense secondary beams. It is highly important to keep the time schedule of the SPES in order to not spoil the discovery potential of the facility.
7 Conclusions
References